Feasibility of Highly Line-Narrowed F_2 laser for 157 nm Microlithography

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ABSTRACT

Highly line-narrowed F_2 laser operation in the VUV has been achieved for the first time by means of a master oscillator/power amplifier (MOPA) laser design. Different concepts have been investigated experimentally for the master oscillator (MO) in order to obtain narrowband spectra. The diffraction grating based design showed to be limited to a FWHM of approx. 0.4 pm. The spectral FWHM of the MO could be further reduced to below 0.3 pm with a double etalon-based resonator. Single pass amplification was employed to increase the beam energy density of the beam up to 50 mJ/cm^2. The spectral FWHM of the amplified light is slightly larger than the FWHM of the correspondent MO radiation, indicating saturation and/or inhomogeneous broadening of the F_2 amplifier medium. Experimental data obtained from broadband operation and ASE measurements suggests that the free running bandwidth of F_2 lasers result from spectral gain-narrowing of the laser medium.

1. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The MO's discharge chamber is driven from a solid state pulsed-power module (SSPPM). Cooling water, fill gas and the blower fan drive are obtained from an industries standard laser frame. The optical interface of the chamber consists of Brewster windows with additional N_2-purge on the outer sides. A closely attached tabletop compartment on the rear side of the chamber allows the variable implementation of experimental optical setups. Several electrical feedthroughs are available for control of internal stepper motor drives used in the diffraction grating based design. At the opposite side of the chamber, either a dielectric mirror output coupler (OC) or an etalon can be mounted. Both of these enclosures are N_2-purged and continuously monitored with an oxygen sensor. The sealing allows operation at ppm-levels of residual oxygen. In order to tune the etalon based designs both enclosures can be pressurized in a controlled manner. A CaF_2 window isolates the MO purge system from all other parts of the setup. The MO beam is directed into a large-size sealed and N_2-purged tabletop box. Before entering the power amplifier (PA), part of the beam is split of to a fast photodetector. Remote actuated flip targets with fluorescent screens can be inserted into the beam path for a coarse analysis and position control. All optical mounts are accessible from outside through glove ports mounted on the acrylic top lid, which also allows to install further or to remove unused optical elements without opening the sealed volume. An optical power meter head can be moved into the beam right in front of the MO. A spectrometer is attached to this tabletop box at another port. A small part of the MO radiation can be directed to the spectrometer aperture by removing a beam stop. The other side of this beam stop holds a partial reflector in order to direct the amplified radiation into the spectrometer. The amplifier consists of separately fired laser whose discharge chamber is directly mounted on the optical table. The exiting beam of the amplifier passes through a second large N_2-purged tabletop box, which also holds an insertable power meter and a fast photodetector. The major part of the beam is U-folded back into the first tabletop box via a sealed beam return tube. The movable beam stop / beam splitter allows the amplifier to be selected for spectral analysis. The employed 1m focal-length grating spectrometer is of an all-reflective design to allow pre-adjustment with a He-Ne laser. As for the tabletop boxes, the spectrometer is N_2-purged with the oxygen concentration being continuously monitored. The spectral resolution is estimated to be about 0.16 pm from the response to the 633 nm He-Ne laser line. Since no calibrated narrowband light source was available in the VUV range we could not determine the slit function of the spectrometer. For this reason all spectral profiles reported herein are raw data and have not been de-convoluted. The synchronization of both laser chambers is achieved by means of variable delays in the main trigger of both SSPPMs. The temporal jitter between both laser systems could be reduced to less than 10 ns.

2. EXPERIMENTAL RESULTS

1. Broadband measurements with the MO

The MO had been initially operated in broadband mode without any wavelength selective optics. Spectral analysis reveals, depending on gas mixture and pressure, that the FWHM of the emitted spectrum may considerably differ from the currently reported values close to 1.1 pm. Since the MO employs a shorter discharge length than our standard length chambers, the gain-length product is lower at comparable discharge conditions. He-buffered gas mixtures generate a FWHM of approx. 1.3 pm, whereas the FWHM with Ne-buffered gas mixtures is less than 1 pm. Reduction of the pump energy further decreases the FWHM bandwidth down to 0.77 pm. However, using neon instead of helium for the buffer gas significantly reduces the efficiency, so that only 210 μJ energy are be obtained at this bandwidth.

2. Broadband amplification measurements

In order to analyze the characteristics of the gain dynamics and saturation of the F_2 power amplifier (PA) system, the MO radiation is injected into the second discharge chamber. The PA is operated with He-buffer for high efficiency, whereas the MO is operated with Ne-buffer in order to slightly reduce the bandwidth. By varying the trigger delay time between MO and PA, the amplifier gain can be sampled in the time domain. Fig. 2 suggests that the temporal gain duration of the F_2 amplifier system is rather short. If the amplifier trigger is advanced the output energy drops rapidly because the inversion density has been depleted before the light passes through the medium. Increasing the delay of the amplifier trigger shows a less pronounced decay, indicating that even low amounts of oscillator radiation are sufficient to extract the energy from the amplifier medium. This is also supported by gain saturation experiments, in which the energy of the MO is varied. Fig. 3 shows that energies in the range of few 10 uJ are sufficient to extract most of the stored energy, indicating that the specific small signal gain of the amplifier medium is very high.

The spectral analysis of both MO and PA radiation reveal that the amplified radiation is slightly broadened. Fig.4 shows the peak-normalized spectra of MO, PA together with the ASE of the PA with the MO disabled during the measurement. Obviously the center wavelength of the amplifiers ASE is shifted by about 0.7 pm with respect to the center of the MO spectrum, which is believed to be caused by different pressure shift coefficients of the two different buffer gases helium and neon. In spite of this de-tuning the MO is capable to pull the PA on its center wavelength, however, with increased bandwidth, indicating inhomogeneous broadening in the amplifier gain. Due to the spectral gain offset between Ne- and He-buffer, additional ASE contributions from the amplifier to the output spectrum might be expected in the long wavelength tail of the spectrum, thereby increasing the FWHM of the spectrum. However, the measured spectra do not show significant increases in that regime, so that the increased bandwidth is more likely due to the above-mentioned broadening mechanism. Consequently, our next step was to install a line-narrowing package (LNP) in the MO resonator, allowing us to inject narrowband radiation in the PA in order to get deeper insight in the broadening mechanism.

3. Line-narrowing of MO with diffraction grating based design

The first approach to line-narrow the MO was to install a diffraction grating based design, similar to the existing LNP design of narrowband KrF and ArF excimer lasers. A four-prism beam expander is employed to reduce the beam divergence on the grating. However, the high gain of the F_2 laser medium requires additional apertures to limit the vertical divergence of the beam incident on the grating, which otherwise deteriorate the spectral resolution. The OC is a 40 % partial reflector. Measurement of the spectrum shows, that the FWHM also depends on the pump energy. Fig. 5 shows the FWHM width of the spectrum versus the high voltage setting of the power supply for two different sets of apertures, which were mounted near the ends of the discharge chamber. The increase in bandwidth with increasing pump energy might be explained by comparing the temporal pulse shape. Fig. 6 shows peak normalized pulse shapes at different pump energy levels. At higher pump energies mainly the first part of the pulse increases, which has not yet undergone sufficient gain narrowing in the medium. At lower pump energy the pulse energy is more equally spread over the pulse duration. Unfortunately, the size of the apertures can not be reduced further, since the MO will not operate with increased losses. The lowest achievable FWHM bandwidth of this setup appears to be limited by roughly 0.4 pm, which is considered as too high for a reasonable analysis of the spectral broadening in the PA.

4. Line-narrowing of MO with etalon (rear side), PA spectrum

The second approach to achieve a higher degree of line-narrowing from the MO was an etalon-based design. The rear side of the MO is equipped with an etalon of an FSR of 0.82 pm. The etalon is pressure-tuned with N_2 to the spectral gain peak of the MO. The front side of the resonator employs a 40 % partial reflector. The MO, operating with Ne-buffer, still performs well

with both resonator apertures being reduced down to 1 mm diameter, which indicates that the losses of the optical elements of this design are somewhat less than the losses from the diffraction grating based design. In order to measure the correct light signals the whole beam path through the amplifier towards the spectrometer is fitted with similar sized apertures. Fig. 7 shows the normalized spectra of the MO and the PA as well. Besides the narrower central part of the spectrum, side modes at +/- of the FSR appear. Also the FWHM bandwidth of the PA increases by about 30 %. Furthermore, the contrast ratio of the central peak to the side modes decreases upon amplification. Both effects suggest inhomogeneous broadening in the PA gain medium. Although the PA is operating with He-buffer, shifting the central gain peak about 0.7 pm from the center of the MO spectrum, the PA spectrum does not show significant asymmetry towards the gain peak of the PA. The energy of the MO is below 20 uJ, which is, unfortunately, the resolution limit of the used laser power meter. The energy density of the amplified beam is about 35 mJ/cm^2.

5. Line-narrowing of MO with twin etalon, PA spectrum

Even narrower spectra are obtained with a twin etalon based MO design, in which the 40 % reflector at the output is replaced by another etalon of the same FSR. Tuning is achieved by controlling the pressure of the N_2 purge on both etalons. Fig. 8 shows the spectral data obtained with this configuration. Again, the FWHM bandwidth and the contrast ratio between peak and side modes degrade upon amplification. The MO output energy is still too low to be precisely measurable with the laser power meter. The energy density of the amplified beam increased up to approx. 50 mJ/cm^2. This increase with respect to the previous experiments might be explained by the higher coupling efficiency of the etalon output coupler. The slightly increased energy from the MO will extract more energy from the PA due to improved saturation, especially in the entrance area of the Pa gain medium.

3. CONCLUSION

Line-narrowing of a F_2 laser below 0.3 pm FWHM has been successfully demonstrated. Although the efficiency of the line-narrowed MO scheme incorporated here is quite low, the very high specific gain of the following F_2 power amplifier allows achieving high specific energy densities of the output beam. The spectral broadening observed upon amplification is attributed to inhomogeneous broadening in the amplifier medium. Improved line-narrowing of the MO with higher spectral purity or appropriate spectral filtering (grating or etalon) of the MO radiation might minimize the increase in bandwidth of the amplified beam.

4. FIGURES

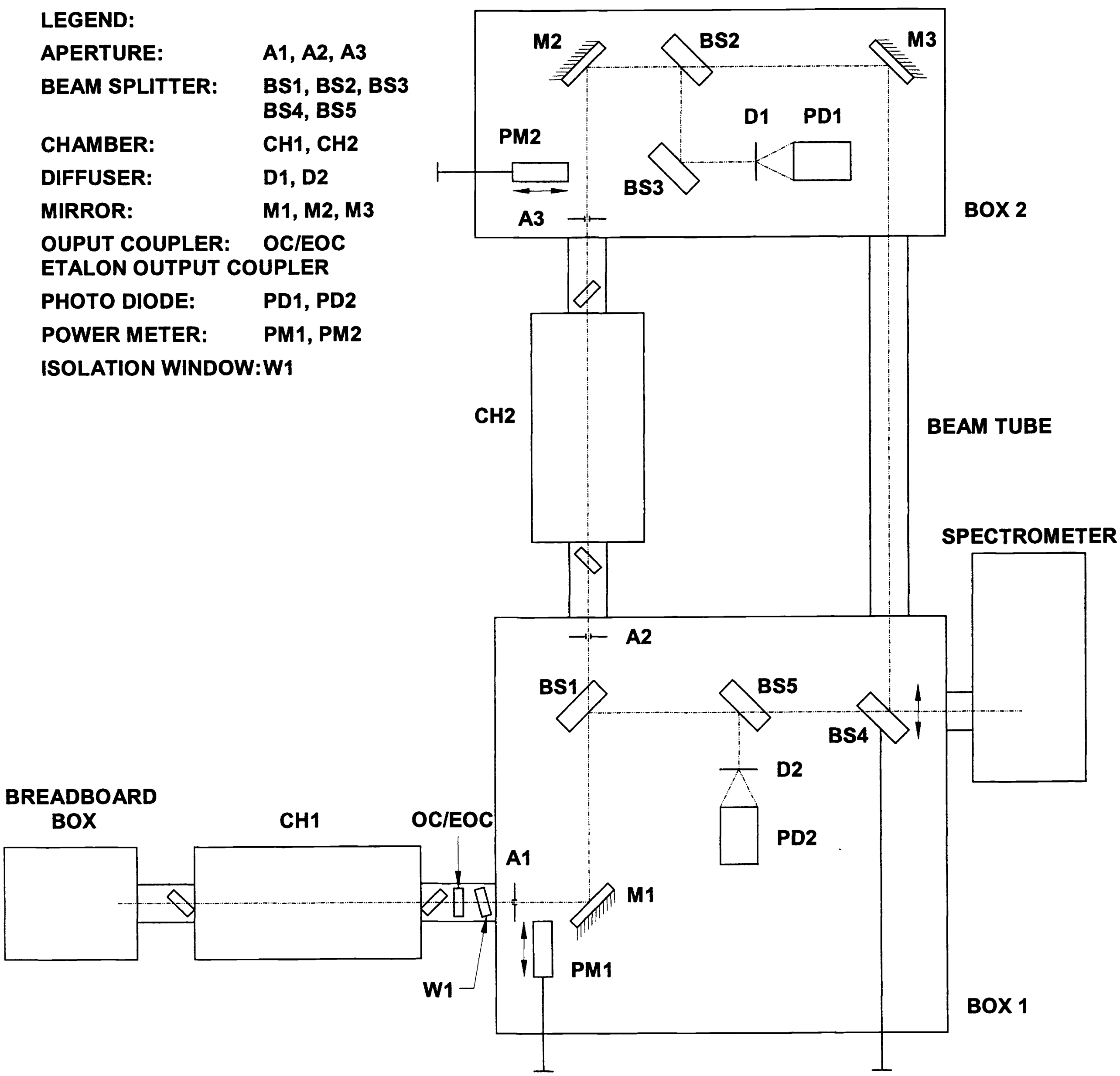

Figure 1: Experimental setup

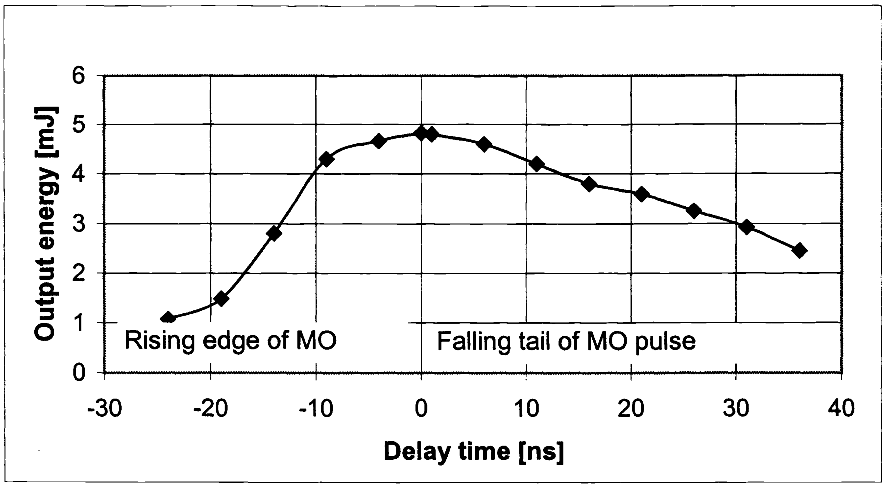

Figure 2: Temporal gain dynamics of F_2 laser medium

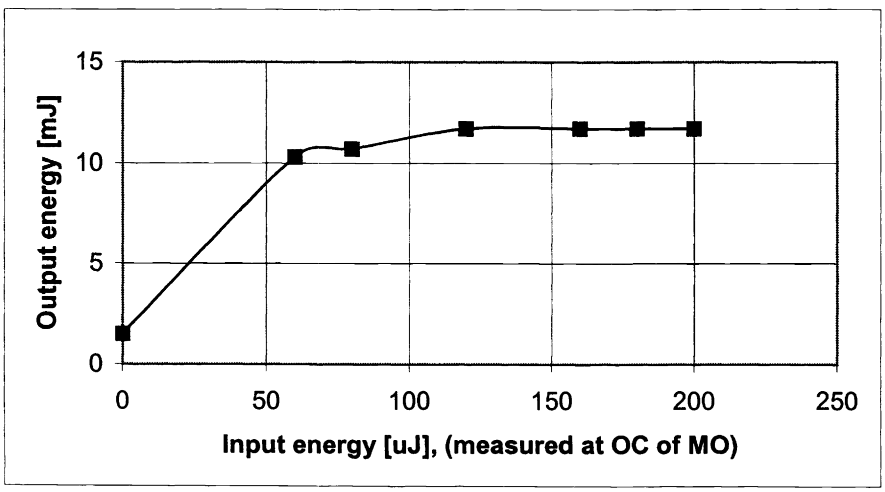

Figure 3: Saturation characteristics of F2 MOPA system

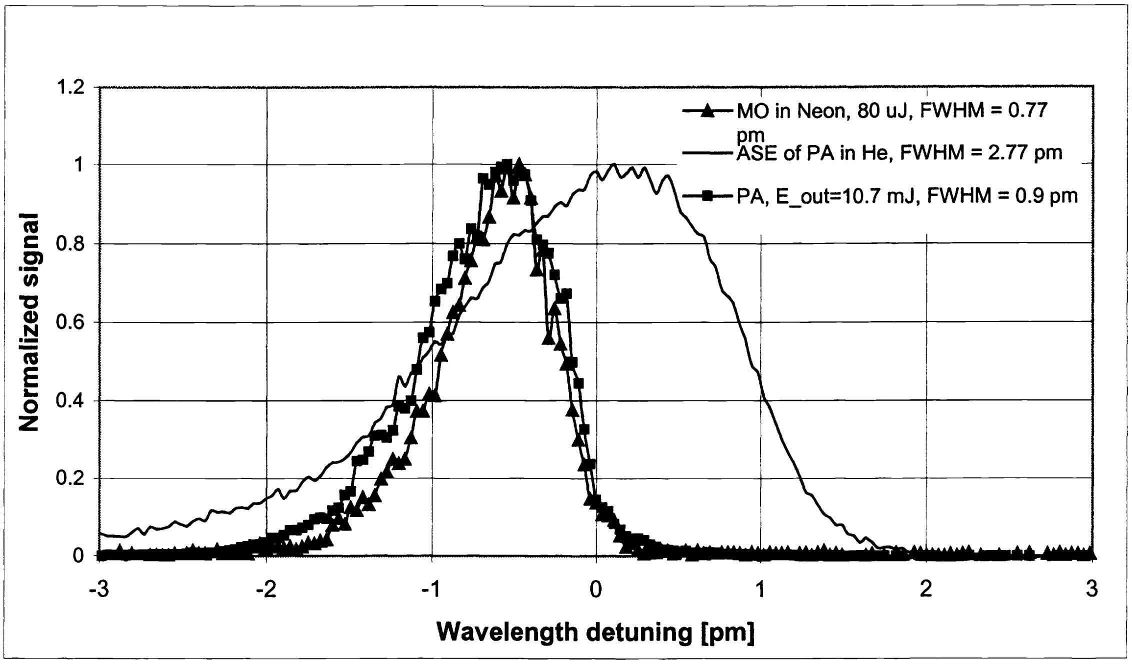

Figure 4: Normalized spectra of MO, PA and ASE of the PA with MO disabled

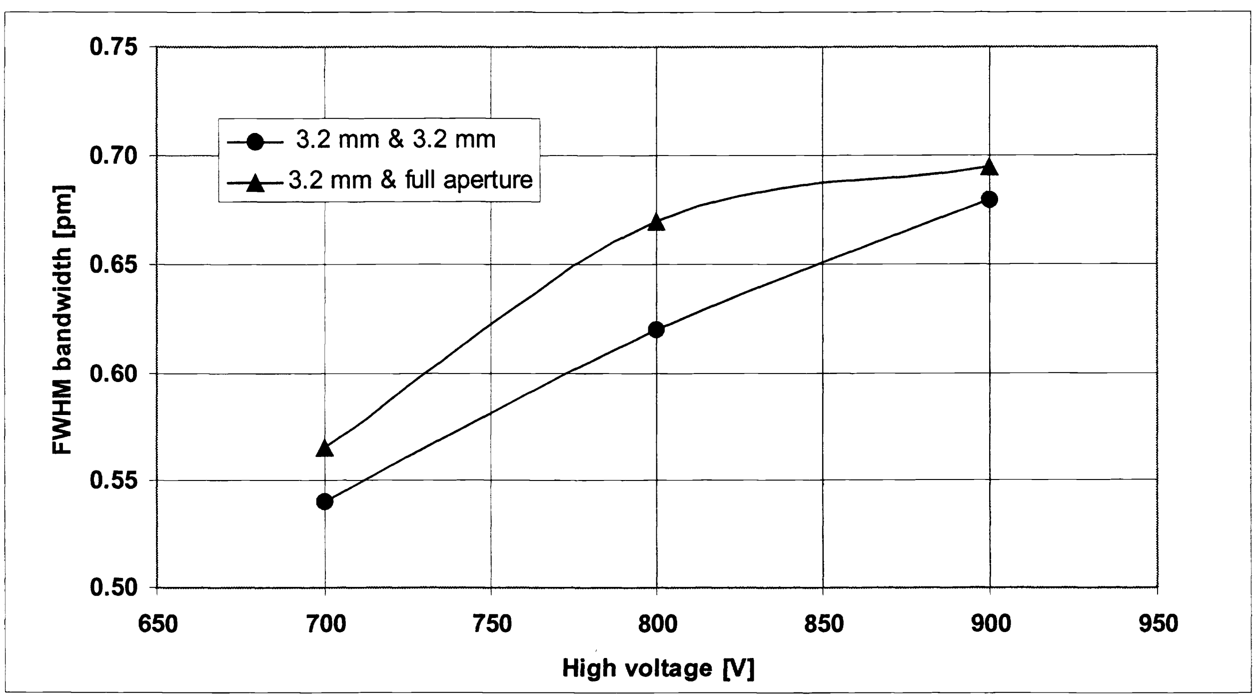

Figure 5: Spectral FWHM versus high voltage of MO power supply

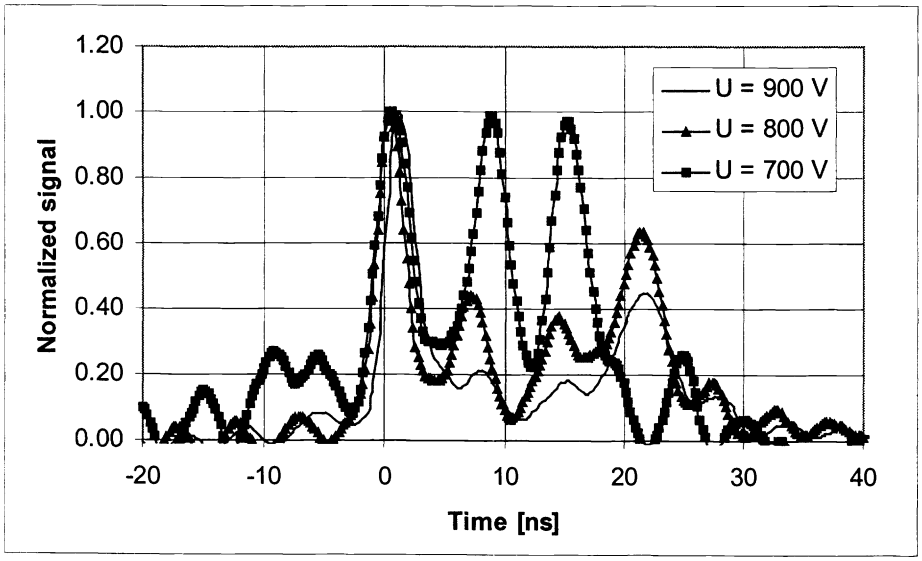

Figure 6: Peak-normalized temporal pulse shape of MO with different pump power

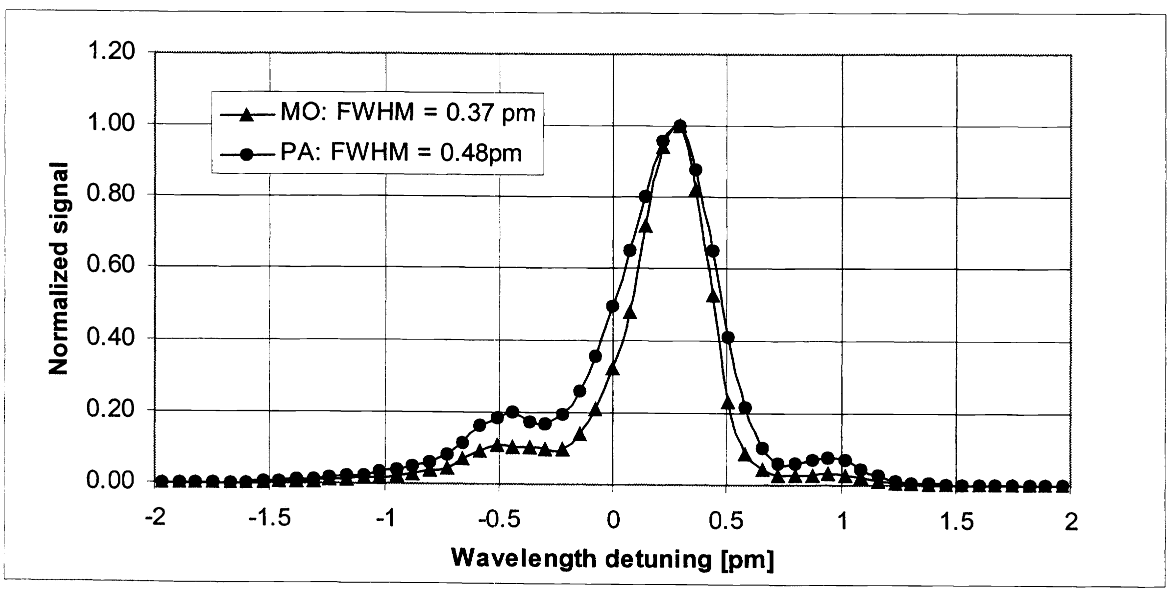

Figure 7: Normalized spectra of single-etalon MO and PA

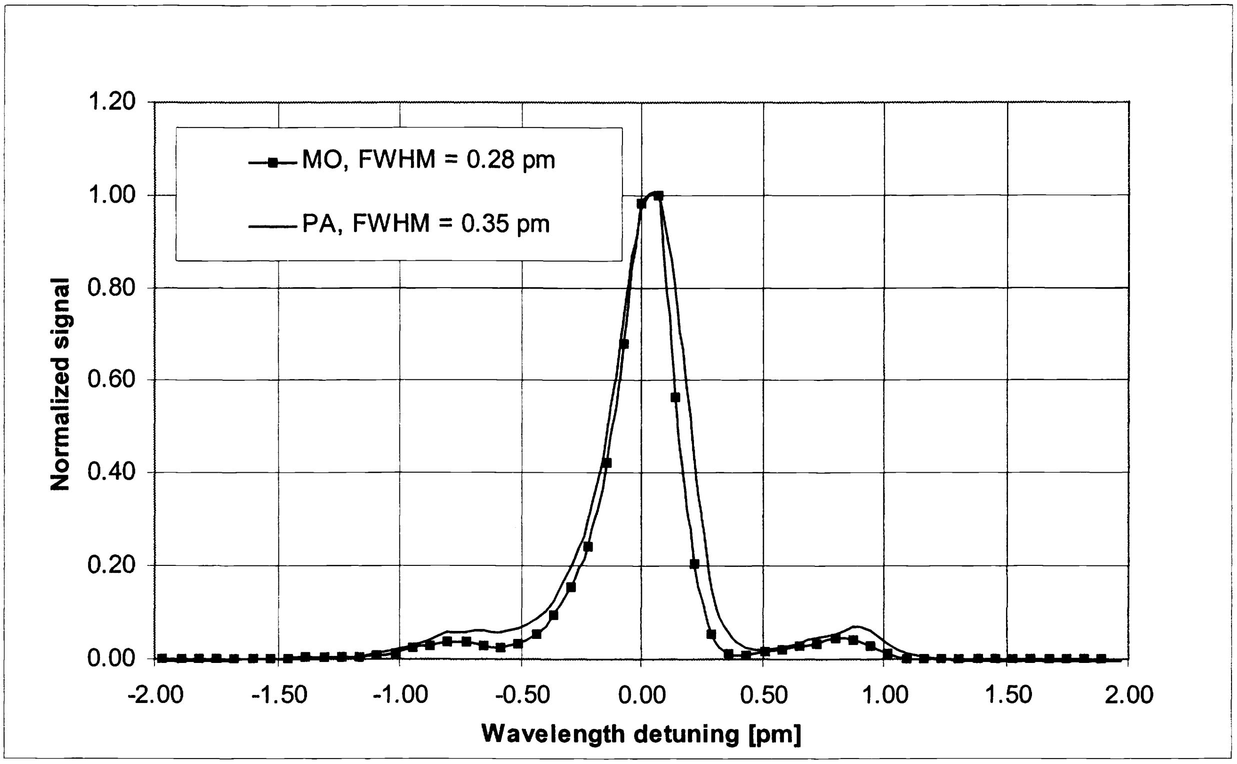

Figure 8: Normalized spectra of twin-etalon MO and PA